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Quasiparticle Excitations outside the Vortex Cores in MgB_2 Probed by Muon Spin Rotation

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The magnetic penetration depth λ in the mixed state of MgB_2 has been determined microscopically from the field distribution around magnetic vortices probed by muon spin rotation. Both the temperature and magnetic field dependence of λ strongly suggest the presence of delocalized quasiparticles around the vortex cores. In particular, the effect of Doppler shift has been clearly observed as a finite gradient of the field dependence of λ, strongly suggesting an anisotropic order parameter with the region of a vanishingly small energy gap.

KEYWORDS: MgB_2, flux-line lattice state, penetration depth, μSR

The revelation of superconductivity in a binary intermetallic compound, MgB_2, has attracted much interest because it exhibits a transition temperature T_c ($\simeq 39$ K) almost two times higher than those of all other intermetallic superconductors known to date.[1] The most interesting issue associated with this compound is whether or not it belongs to the class of conventional Bardeen-Cooper-Schrieffer (BCS) type superconductors. To date, most experimental results have favored a phonon mediated superconductivity. The boron isotope effect,[2] photoemission spectroscopy,[3] ^{11}B-NMR,[4] Raman spectroscopy,[5] tunneling measurements,[6–9] and optical conductivity data[10] are all consistent with the conventional BCS s-wave pairing. On the other hand, calculations of the band structure and the phonon spectrum predict a double energy gap,[11,12] a larger gap attributed to two-dimensional p_{x-y} orbitals, and a smaller gap attributed to three-dimensional p_z bonding and antibonding orbitals. Experimental results of specific heat measurements,[13,14] point-contact spectroscopy,[15] photoemission spectroscopy,[16] scanning tunneling spectroscopy[17] and penetration depth measurements[18] have supported this scenario.

It must be noted that earlier experiments including muon spin rotation (μSR)[19] and ac susceptibility[19,20] performed on polycrystalline samples revealed a quadratic behavior of λ at low temperatures, from which they inferred the presence of line nodes in the order parameter. However, the recent μSR analysis has demonstrated that such behavior can also be explained by assuming the double energy gap (without resorting to the line nodes).[21] Thus, the temperature dependence of λ provides limited information for determining the structure of the order parameter. This situation can be improved by studying the magnetic field dependence of λ, where the quasiparticle excitation is controlled by the Doppler shift[22] which is independent of the thermal excitation. In order to obtain more detailed information on the order parameter in MgB_2, we have observed the field dependence of λ over a wide range of magnetic field up to 5 T.

The magnetic penetration depth λ is determined by the quasiparticle excitations outside the vortex cores, and thus it provides an excellent measure of the structure of the order parameter in the flux-line lattice (FLL) state. The μSR technique is a powerful microscopic tool for obtaining the fundamental length scale such as λ in the bulk type II superconductors. Implanted muons randomly probe the local magnetic fields induced by the FLL, yielding the spectral density $n(B)$ which is directly related to the spatial field distribution $B(r)$. While the μSR spectra in a single crystalline specimen can be compared directly with $n(B)$ calculated from the spatial field distribution $B(r)$, the spectra in a polycrystalline specimen are subject to the modulation of line shape due to various kinds of inhomogeneity. Even in such a situation, the time-dependent μSR spectra is approximately described by a Gaussian damping $\exp(-\sigma^2t^2/2)$ with σ being primarily determined by the second moment of $n(B)$.

In this letter, we report on the temperature and field dependence of λ deduced from those of σ in polycrystalline MgB_2. A special precaution has been taken in selecting the field for the temperature scan, in order to avoid the effect of random flux pinning near the lower critical field H_{c1}. Analysis based on the two-gap model yields $\Delta_1 = 4.9(1)$ meV and $\Delta_2 = 1.2(3)$ meV. The penetration depth at $T = 0$ K is estimated to be 103.9(1.0) nm. We also found that λ at $T \simeq 10$ K exhibits a significant increase with almost linear dependence on the applied magnetic field, which can be understood by considering the Doppler shift of the quasiparticle excitation associated with the anisotropic order parameter.[22] However, the gradient against the field is considerably small compared with that in d-wave superconductors. These results indicate the existence of excess quasiparticle excitations outside the vortex cores in MgB_2, strongly suggesting that there is an anisotropic structure in the

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order parameter with a nodal region smaller than that for the d-wave pairing.

The polycrystalline sample of MgB_2 used in this experiment had a surface area of $\sim$ 50 mm^2. The superconducting transition temperature T_c determined from resistivity and susceptibility measurements was 38.5 K.[1)] μSR experiment was performed on the M15 beamline at TRIUMF which provides a muon beam with the momentum of 29 MeV/c. A muon-veto counter system was adopted to eliminate positron events from muons which missed the sample so that the relative yield of such events was less than 5% of the total positron events. An experimental setup with a high time resolution was employed to measure the transverse field (TF-) μSR time spectra up to 5 T. The sample was field cooled at the measured magnetic fields in order to eliminate the effect of flux pinning.

Since the muons stop randomly on the length scale of the FLL, the muon spin precession signal $\hat{P}(t)$ provides a random sampling of the internal field distribution $B(r)$,

$$\hat{P}(t) \equiv P_x(t) + iP_y(t) = \int_{-\infty}^{\infty} n(B)\exp(i\gamma_\mu Bt)dB, \quad (1)$$

$$n(B) = \frac{dr}{dB}, \quad (2)$$

where γ_μ is the muon gyromagnetic ratio ($= 2\pi\times 135.53$ MHz/T), and $n(B)$ is the spectral density determined by the local field distribution. These equations indicate that the real amplitude of the Fourier transformed muon precession signal corresponds to the spectral density $n(B)$. The London penetration depth in the FLL state is related to the second moment $\langle(\Delta B)^2\rangle$ of $n(B)$ reflected in the μSR line shape.[23)] For polycrystalline samples, a Gaussian distribution of local fields is a good approximation, where

$$\hat{P}(t) \simeq \exp(-\sigma^2 t^2/2)\exp(i\gamma_\mu Ht) \quad (3)$$

$$\sigma = \gamma_\mu\sqrt{\langle(\Delta B)^2\rangle}, \quad (4)$$

with H being the external magnetic field. For the case of an ideal triangular FLL with the isotropic effective carrier mass m^* and a cutoff $K \approx 1.4/\xi_v$ provided by the numerical solution of the Ginsburg-Landau theory, the London penetration depth λ can be deduced from σ using the following equation:[23)]

$$\sigma\ [\mu\mathrm{s}^{-1}] = 4.83\times 10^4(1-h)[1+3.9(1-h)^2]^{1/2}\lambda^{-2}\ [\mathrm{nm}], \quad (5)$$

where $h = H/H_{c2}$. It should be noted that eq. (5) provides the field dependence of σ when λ is a constant. Here, λ is related to the superconducting carrier density n_s as follows:

$$\lambda^2 = \frac{m^*c^2}{4\pi n_s e^2}, \quad (6)$$

indicating that λ is enhanced upon the reduction of n_s due to the quasiparticle excitations.

Figure 1 shows the fast Fourier transforms (FFT) of the muon precession signal in MgB_2 for different temperatures at $H \simeq 0.5$ T, where the real amplitude of FFT corresponds to $n(B)$ in the FLL state convoluted with additional damping due to small nuclear dipolar fields. As is most explicit in the FFT spectrum at $T = 8.5$ K, the line shape is characterized by a broad peak near $B - H \sim 0$ and a satellite at lower field (with a small background peak right at $B = H$). This is a typical feature often seen in polycrystalline powder samples with a lower Meissner fraction, where the sample consists of both superconducting and normal domains with the typical size of a few microns ($\geq \lambda$). The magnetic field distribution at the normal domain is shifted to a high field because of the demagnetization associated with the Meissner effect in superconducting domains. Thus, the peak at the lower field corresponds to the signal from the superconducting domains.

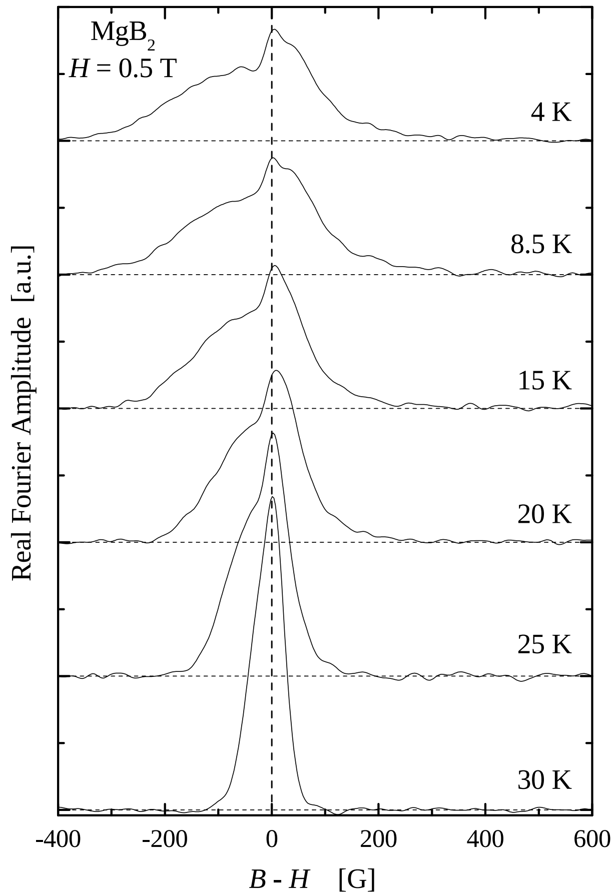

Fig. 1. FFT spectra of μSR signal in MgB_2 at $H \simeq 0.5$ T under several temperatures.

Considering the double peak structure in the FFT spectra in Fig. 1, we adopted two components with the following empirical form for analyzing the data in the time domain:

$$A_0\hat{P}(t) = \sum_{j=1,2} A_j(t)\exp[i(\gamma_\mu B_j t + \phi)], \quad (7)$$

$$A_j(t) = A_j \exp\left[-(\sigma_j t)^2/2\right], \quad (8)$$

where A_0 is the total positron decay asymmetry, A_j ($j = 1, 2$) the partial asymmetry for respective components, B_j the central frequencies, ϕ the initial phase, and σ_j the muon depolarization rates.

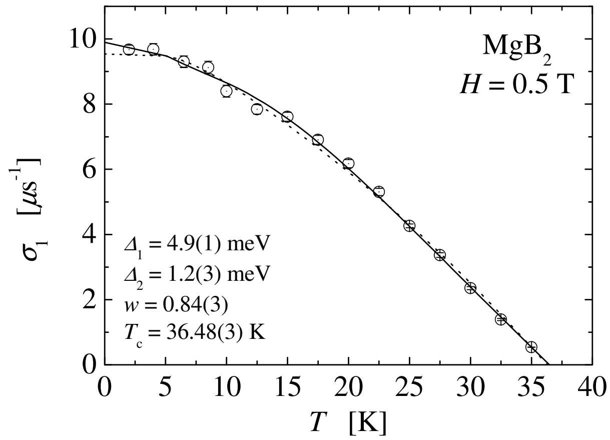

Fig. 2. Temperature dependence of the muon depolarization rate σ_1 under $H = 0.5$ T. The solid curve is the result of fitting by eq. (9).

We show the temperature dependence of the muon depolarization rate σ_1 (which corresponds to the linewidth of the lower frequency peak in Fig. 1) in Fig. 2. These data were obtained under a field $H \simeq 0.5$ T which is well above $H_{c1} \sim 10^{-2}$ T. Following the results of specific heat,[13,14] Raman[5] and μSR measurements,[21] the data were fitted by the two-gap model[24] which is described as follows:

$$\sigma(T) = \sigma(0) - w \cdot \delta\sigma(\Delta_1, T) - (1-w) \cdot \delta\sigma(\Delta_2, T), \quad (9)$$

$$\delta\sigma(\Delta, T) = \frac{2\sigma(0)}{k_B T} \int_0^\infty f(\varepsilon, T) \cdot [1 - f(\varepsilon, T)] d\varepsilon, \quad (10)$$

$$f(\varepsilon, T) = \left(1 + e^{\sqrt{\varepsilon^2 + \Delta(T)^2}/k_B T}\right)^{-1}, \quad (11)$$

where w is the ratio of gap energy between the two gaps, k_B the Boltzmann constant, $f(\varepsilon, T)$ the Fermi distribution of quasiparticles, and $\Delta(T)$ the BCS gap energy.[25] The solid line in Fig. 2 is the best fit result with $\Delta_1 =$ 4.9(1) meV, $\Delta_2 = 1.2(3)$ meV, $w = 0.84(3)$ and $T_c =$ 36.48(3) K. The dotted line shows the result of fitting using the values of Δ_1, Δ_2 and w in ref. 21. Although our result shows reasonable agreement with the earlier one,[21] the value of Δ_2 is considerably smaller than the reported value of 2.6(2) meV.

Figure 3(a) shows the magnetic field dependence of the muon spin relaxation rate σ_1 with an inset showing the low field region ($H < 0.6$ T). As seen in the earlier report,[21] the effect of random flux pinning is observed as a peak of σ_1 in the low field region (see inset of Fig. 3(a)). However, σ_1 decreases with increasing field above $H =$ 0.1 T, indicating that the distortion of FLL is reduced by increasing inter-vortex interaction and that the depolarization is predominantly determined by the intrinsic $n(B)$. The dashed line in Fig. 3(a) shows the fitting result by eq. (5) with $H_{c2} = 12.5$ T as determined by resistivity measurements.[26] (Here, we discuss the magnetic field dependence of σ_1 for the data above $H = 0.5$ T to avoid the remnant effect of flux pinning at lower fields.) Compared with the field dependence of σ_1, the dashed line does not reproduce the data, indicating that λ is not a constant but it increases with increasing external field.

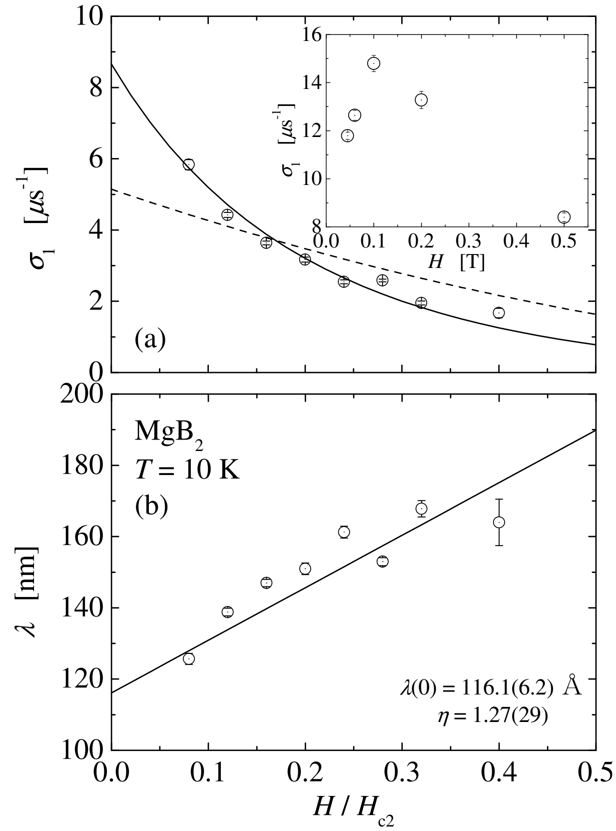

Fig. 3. Magnetic field dependence of (a) the muon depolarization rate σ_1 and (b) the magnetic penetration depth λ at $T \simeq 10$ K. Dashed and solid lines are the fittings using (a) eq. (5) with a constant λ or λ proportional to $\lambda(0)[1 + \eta \cdot h]$ and (b) eq. (12). H_{c2} at this temperature is approximately 12.5 T.

The field dependence of λ estimated from eq. (5) is shown in Fig. 3(b). It clearly exhibits a strong field dependence where $\lambda(h)$ increases almost linearly with h. This is similar to the cases of YNi_2B_2C,[27] $NbSe_2$[28] and high-T_c cuprate superconductors,[29] where the increase of λ is attributed to the anisotropic order parameters and the associated nonlinear effect due to the Doppler shift of the quasiparticles in the nodal region ($\Delta(k) \simeq 0$).[22] The field dependence of λ is expected to be stronger when the phase space satisfying $\Delta(k) \simeq 0$ has larger volume.[30] A fitting by the relation

$$\lambda(h) = \lambda(0)[1 + \eta \cdot h] \quad (12)$$

provides a dimensionless parameter η which represents the strength of the pair breaking effect. We obtain $\eta =$ 1.27(29) with $\lambda(0) = 116.1(6.2)$ nm which is shown as the solid line in Fig. 3(b). The obtained value of η is intermediate between that in YNi_2B_2C and $NbSe_2$ (e.g., $\eta =$ 0.97 at $0.2T_c$,[27] $\eta = 1.61$ at $0.33T_c$,[28] respectively) and is smaller than those in d-wave superconductors (e.g., η $= 5.5 \sim 6.6$ for cuprates[29]). The solid line in Fig. 3(a) is the result of fitting with the relation of eq. (5), with λ represented by eq. (12).

Our result on the temperature dependence of λ is qualitatively consistent with earlier results,[21] suggesting that the order parameter in MgB_2 may be effectively described by adopting the two-gap model. However, the

observed field dependence of λ is not expected for the isotropic order parameter irrespective of the multiplicity of the band structure and the associated gap energy. Considering that the current result on the field dependence of λ was obtained at $T \simeq 10$ K, this energy scale of $\varepsilon \equiv k_BT \sim 1$ meV places an upper boundary on the smaller gap energy Δ_2 in order to explain the observed effect of the Doppler shift. Since our estimation for $\Delta_2 = 1.2(3)$ meV is very close to ε, the observed H-linear behavior of λ may be attributed to the quasiparticle excitations in the vicinity of the smaller gap. While this cannot be distinguished from the case of a nodal structure in the order parameter (i.e., considering a region where $\Delta(k) \ll \varepsilon$), our result is clearly inconsistent with the two-gap model with $\Delta_2 \gg \varepsilon$. On the other hand, it is also quite unlikely that the d-wave pairing is realized in MgB_2, because the coefficient η is much smaller than those in high-T_c cuprates. The recent observation that the order parameter in YNi_2B_2C (where the pairing symmetry has been identified as s-wave[31]) has point nodes[32] exhibits a good correspondence with the intermediate value of $\eta(\sim 1)$ obtained by μSR,[27] suggesting that there is a similar situation in MgB_2. Thus, the present μSR result leads us to conclude that the order parameter in MgB_2 has a structure with an energy gap smaller than $\varepsilon \simeq 1$ meV. The field dependence of λ measured at a much lower temperature would provide more useful information to distinguish the anisotropic order parameter from the isotropic one described by the two-gap model.

In summary, we have performed TF-μSR measurements in MgB_2 to obtain the temperature and magnetic field dependence of the penetration depth λ and the associated spin relaxation rate σ_1. Our result is perfectly in line with the presence of an anisotropic order parameter with a nodal structure, and it sets an upper boundary $\varepsilon \simeq 1$ meV for the smaller gap energy in the two-gap model. The magnetic field dependence of λ exhibits a linear dependence on the external field up to 5 T with the gradient η being considerably smaller than that in d-wave superconductors, which may disfavor the occurrence of d-wave pairing in MgB_2.

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